Design of Closed Loop Lcl-T Resonant Dc-To-Dc Converter Using Different Controllers

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ABSTRACT: *The aim of this study is to simulate the closed loop controlled DC-DC converter for stand-alone wind energy system for different controllers. Wind turbines, are not always very efficient in the wind speeds that are most common to a region. Typically, wind energy systems are designed to be highly efficient in high wind speed and have a cut-off wind speed- below which no energy is captured. Therefore, for the efficient capture of wind power, turbine speed should be controlled to follow the ideal TSR, with an optimal operating point, which is different for every wind speed. The LCL-T resonant inverter system for closed loop DC-to-DC converter systems are simulated using MATLAB Simulink power system blocks for different controllers. This converter has advantages like reduced transformer size, reduced filter size and current source characteristics. The simulation studies indicate that LCL-T type for closed loop DC-DC converter can be used with stand-alone wind generator. Constant voltage can be maintained at the output of DC-to-DC converter by using a PWM rectifier at the output.*
Keywords: Converters, Resonant Inverters, DC-DC Converter, MATLAB.

I.   INTRODUCTION

Small-scale stand-alone wind energy is increasingly viewed as a viable and sometimes preferred source of electrical energy. Consider, for example, remote villages in developing countries or ranches located far away from main power lines. Wind energy is a quiet alternative to remote diesel generation- that sometimes depends on excessive transportation and fuel storage costs- and an economically justifiable alternative to a grid connection. Wind energy is a quiet alternative to remote diesel generation- that sometimes depends on excessive transportation and fuel storage costs- and an economically justifiable alternative to a grid connection. It has been shown that a remote load has only to be a matter of a few miles away from a main power line for a stand-alone wind generator to be cost-effective (Kellogg et al., 1998). A typical, small-scale, stand-alone, wind electric system is composed of a wind turbine, a permanent-magnet generator, a diode bridge rectifier and a dc power system. In many small-scale systems, the dc system is at a constant dc voltage and is usually comprised of a battery bank, allowing energy storage, a controller to keep the batteries from overcharging and a load. The load may be DC or may include an inverter to an AC system. The load configuration is beyond the scope of this study.Unfortunately, there can be significant problems connecting a wind generator to a constant DC voltage. At low wind speeds, the induced voltage in the generator will not be high enough to overcome the reverse bias in the diode bridge. At high wind speed, the electrical frequency increases and the reactive impedance of the generator will be high, while the impedance of the battery load will be low. In this case, the poor impedance matching will limit power transfer to the DC system (Yamamura et al., 1999; Borage, 2005; Daniel and Gounden, 2004; Arutchelvi and Daniel, 2006; 2007). Control of the DC-DC converter may be achieved by means of maximum power point tracking (Daniel and Gounden, 2004) or by means of a pre-determined relationship between wind speed and rectifier DC voltage (Arutchelvi and Daniel, 2006; 2007). Maximum power point tracking requires continuous variation of the DC voltage to determine whether the output power may be increased. This system is relatively complex. The relatively high turbine inertia can cause a significant time lag between the changes to the DC-link voltage and any observed change in power. Use of a predetermined relationship between wind speed and voltage may also have difficulties. Accurate wind speed measurement is difficult and requires the use of a relatively expensive anemometer if it is to be used for system control. The system proposed in this study makes use of a predetermined relationship between generator electrical frequency and DC-link voltage. Three ports triple half bridge bidirectional converters with zero voltage switching are given in (Tao and Hendix, 2008). Fuel cell and super capacitor are used as sources. Active snubber cell for DC to DC converter is given in (Hosseni and Moradi, 2008).

This study deals with a LCL-T resonant DC-DC converter that achieves constant wind turbine efficiency across a wide range of wind speeds for different controllers. The system is designed for use in remote location and, therefore, includes a simple control strategy and a fault- tolerant topology. The control circuit included fault detection and has been tested with a parallel redundant DC link. Previously published works demonstrated the ability of the control system to detect both open- and short-circuit converter faults and switch to a parallel converter without interruption of the supply. The literature (Kellogg et al., 1998) to (Hosseni and Moradi, 2008) does not deal with the simulation of closed loop controlled DC-to-DC converter. This study deals with closed loop controlled DC-to-DC converter. This study also compares the experimental results with the simulation results. The system represented in the Figure. 1 where VDC is a variable voltage and VBATT is a fixed DC voltage.
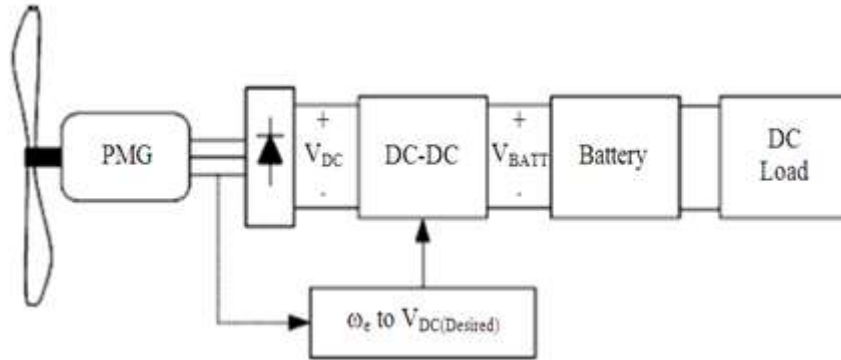
Figure. 1. Schematic diagram of the stand-alone wind Energy system under consideration

II. THEORETICAL APPROACH

The fundamental equation governing the power capture of a wind turbine is Equation 1:

$$P_t = \frac{1}{2}\rho A C_p v_w^3 \qquad (1)$$

where, Pt is turbine power, ρ is air density, A is the swept turbine area, Cp is the turbine coefficient of performance and $v_{\acute{\omega}}$ is wind speed. The coefficient of performance is a function of TSR, described by Equation 2:

$$TSR = \frac{r\omega_m}{v_\omega} \qquad (2)$$

Where, ω_m is rotational speed, is the turbine radius and is wind speed. The maximum power captured by the wind turbine will occur when the TSR is approximately 7.5, corresponding to an of 0.35. A typical Cp curve shown in Figure 2.
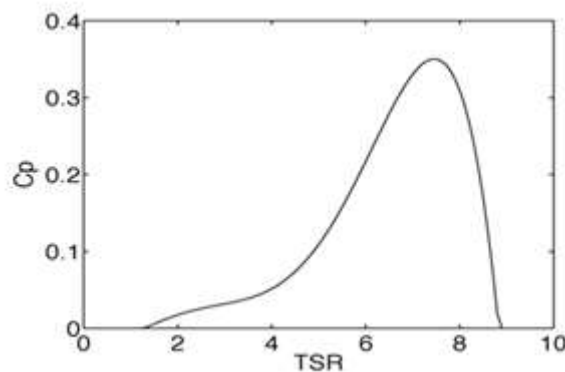

Figure.2. Typical Cp curve

A relatively small deviation on either side of this TSR will result in a significant reduction of the power available for conversion to electrical energy. Employing control of the rotational speed of the turbine allows the TSR to be controlled and the coefficient of performance to be maximized. Thus, in turn, the generated

electrical energy may be maximized. Control over the rotational speed is achieved by varying the generator terminal voltage.

A simple understanding of the ideal steady-state relationship between terminal voltage and rotational speed may be obtained by considering a generator with a fundamental current in phase with terminal voltage and neglecting harmonic currents.

An approximation of the rectified dc-link voltage may be obtained using the standard equations for a three-phase full-bridge diode rectifier with line inductance. It is possible to obtain a prediction for dc-link voltage as a function of mechanical speed (or electrical generated frequency) and TSR. In the ideal case, the generator operates at the peak of the curve.

III. DESIGN CALCULATIONS

48V/12V transformer, fs = 20 KHz, fr = 56 KHz, φ = 10μwb, Lr = 9μH, RL = 100Ω, r = 7e-4. The following assumptions are made:

(i) Saturation is neglected.

(ii) Magnetizing current is neglected Equation 3-5:

Using $E_1 = 4.44 \times N_1 \times \varphi \times f$

We obtain $N_1 = 54$ (3)

Using $E_1 = 4.44 \times N_1 \times \varphi \times f$

We obtain $N_1 = 13$ (4)

Using $f_r = 1/2\pi\sqrt{L_r C_r}$

We obtain $C_r = 0.75\mu F$ (5)

Using $r = 1/4\sqrt{3} \times f \times C \times R_L$

We obtain $C = 100\mu F$ (6)

The equation of inverter is as follows Equation 7-8:

$V_O = V_D$ for $0 < t < T/2$ (7)

$V_O = -V_D$ for $T/2 < t < T$ (8)

The ripple factor of the rectifier is Equation 9:

$r = 1/4\sqrt{3}Fcr$ (9)

IV. SIMULATION RESULTS

Simulation is done using MATLAB and the results are presented here. DC-DC converter is shown in figure 3a. 48V DC is converted into AC using full bridge inverter. Soft switching is obtained by introducing LCL circuit. 48V AC is stepped down to 5V AC by using step down transformer. The output of transformer is rectified by using a diode rectifier and capacitor filter. Scopes are connected to display the driving pulses, inverter output and DC output. DC input voltage is shown in figure 3b. DC output voltage and current waveforms are shown in Figure 3c. It can be seen that the output is free from ripple.
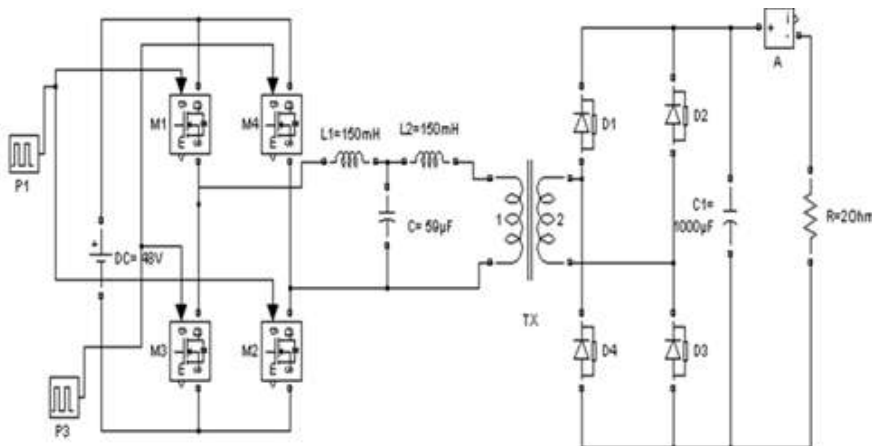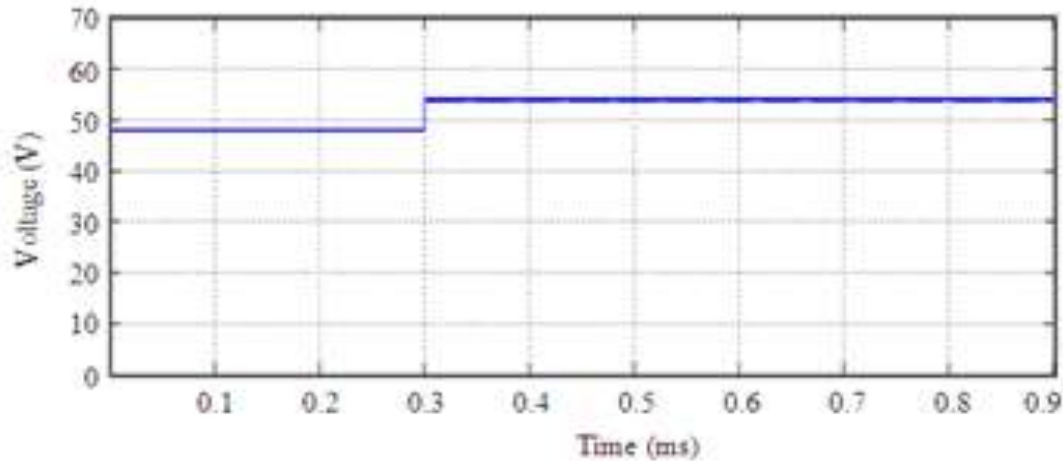

Figure.3a. DC-DC converter circuit
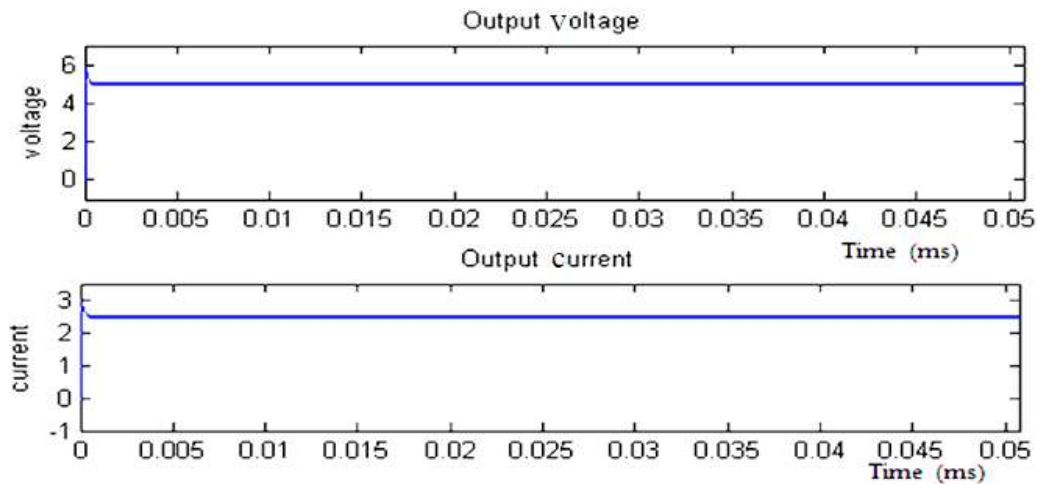
Figure.3b. DC Input Voltage

Figure.3c. DC Output Voltage & Output Current

V. CLOSED LOOP SYSTEM FOR DIFFERENT CONTROLLERS

Open loop system with disturbance is shown in figure 4a. Disturbance source is represented as a subsystem. A step increase in input voltage is applied. The input voltage with disturbance is shown in figure 4b. The output voltage with disturbance is shown in figure 4c. The output voltage also increases in open loop system. The output current waveform shown in figure 4d. LCL-T Closed loop system has been designed for PI controller for reducing the steady state error. Here it has been compared with the different types of controllers like P and PID with respect to the steady state error. The Figures 4e and 4f show the closed loop system of P controller and output waveform. It reaches the steady state condition quickly. Figures 4g shows the LCL-T resonant converter for closed loop system with PI controller. The output voltage and current waveforms for PI controller are shown in Figure 4h and 4i. It is observed that the steady state error is reduced. Figure 4j shows the closed loop system with PID controller. The output voltage and current waveform for PID controller is shown in figure 4k and 4l. It observed that the steady state error and the settling time are reduced. The output voltage is sensed and it is compared with a reference voltage of 5V. Thus the closed loop system is capable of reducing the steady state error. The parameters of $K_P = 4$ and $K_I = 0.1$ are used for simulation studies.
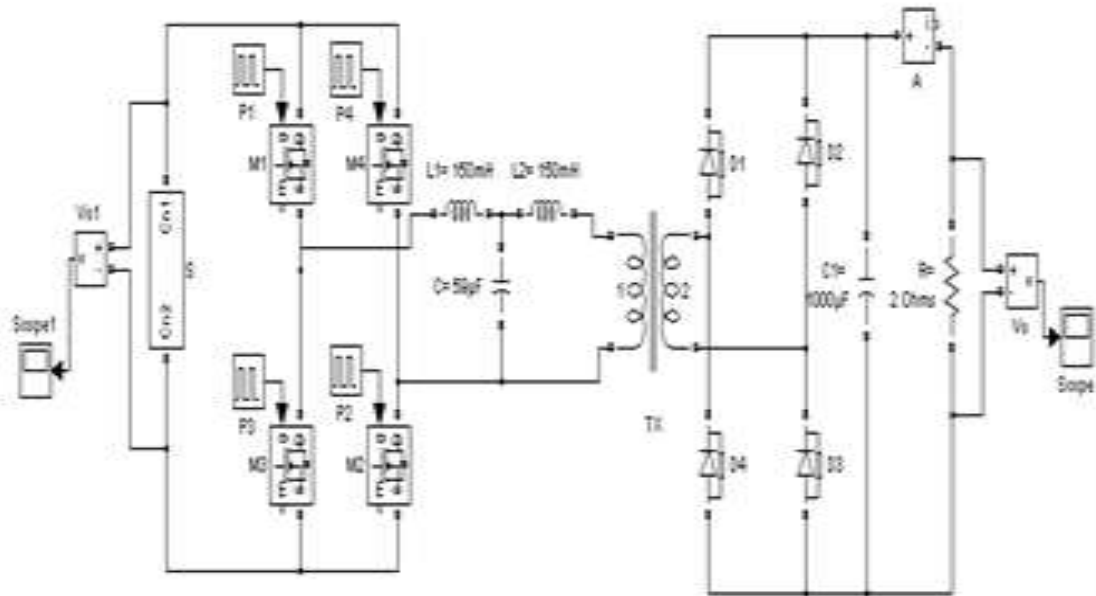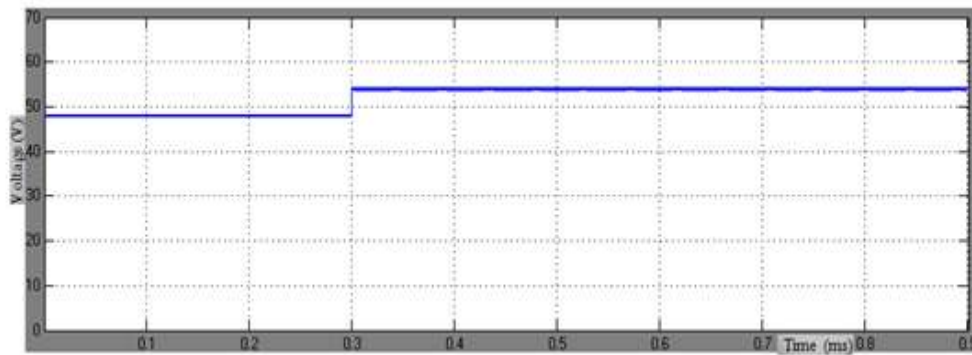
Figure.4a. Open Loop System with a Disturbance

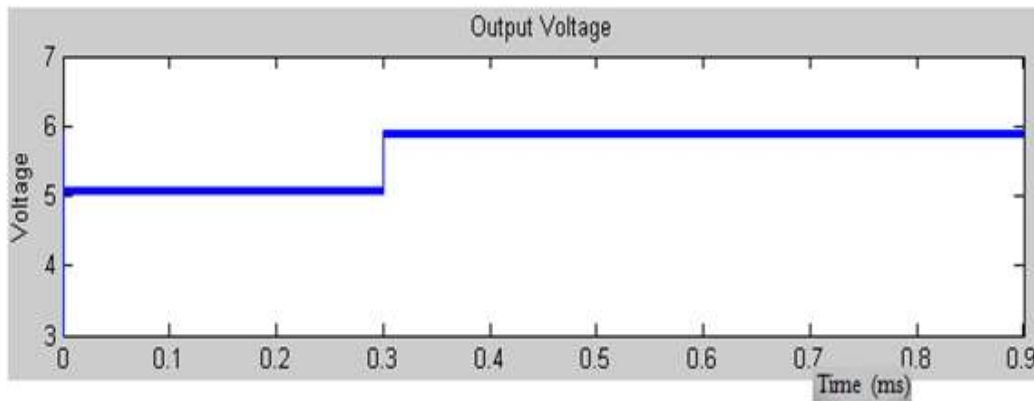**Figure.4b. Input Voltage with Disturbance**

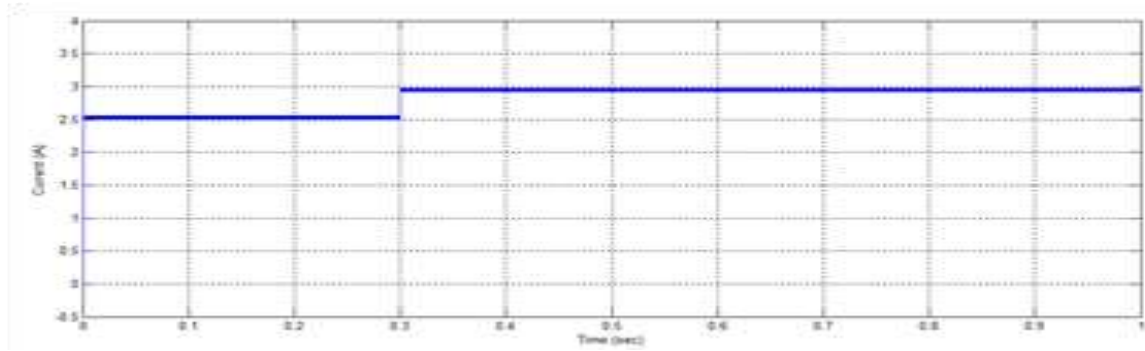**Figure.4c. Output Voltage of Open loop system**
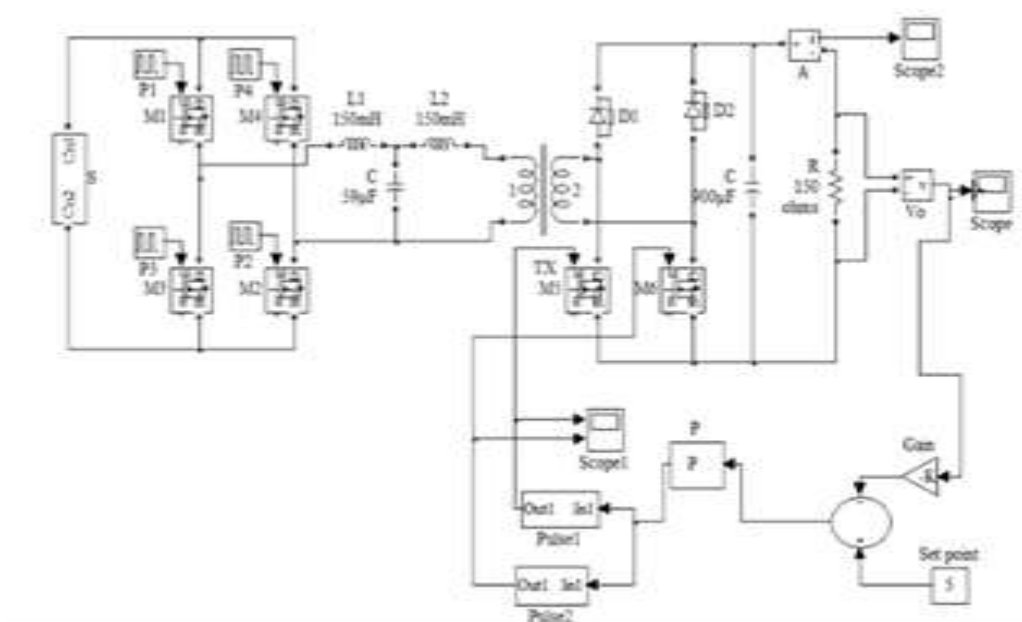
Figure.4d. Output Current waveform

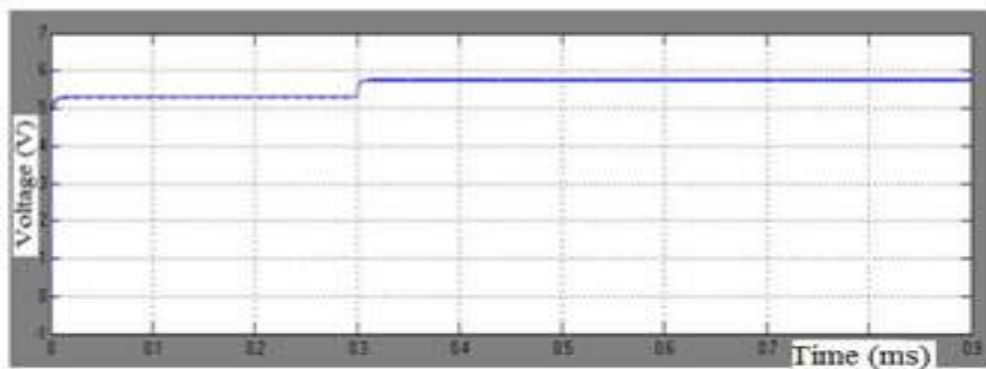**Figure.4e. Closed Loop System for P controllers**

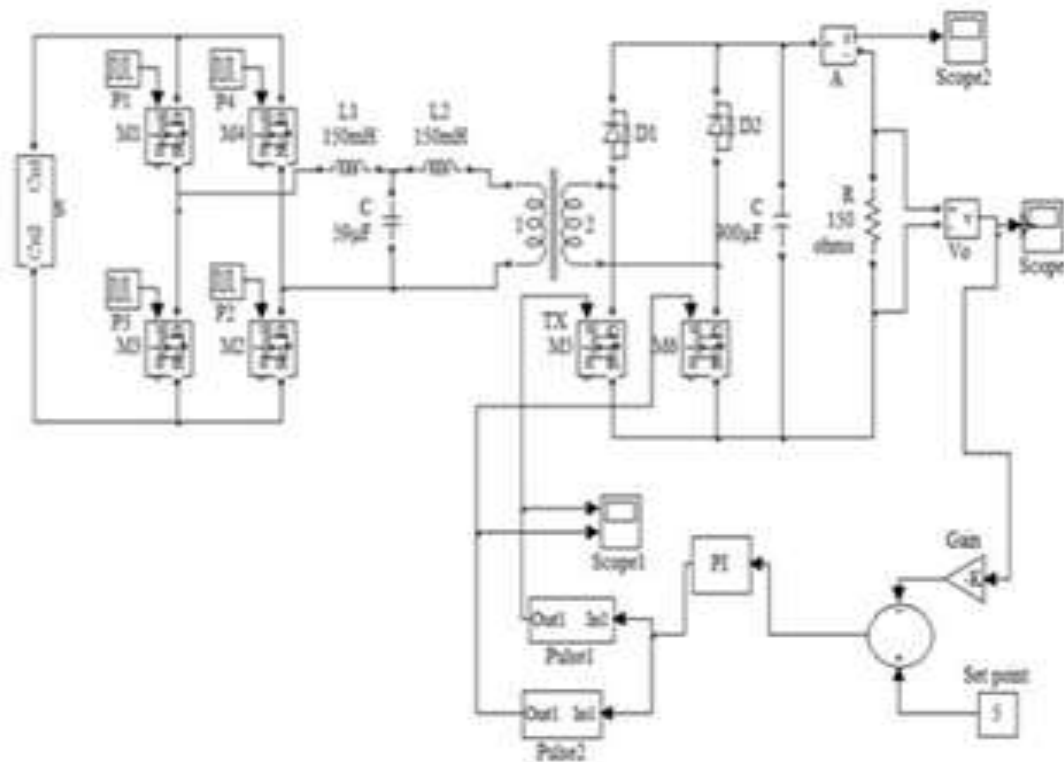**Figure.4f. Output Voltage waveform for P controllers**

Figure.4g. LCL -T Resonant Converter with the PI Controller
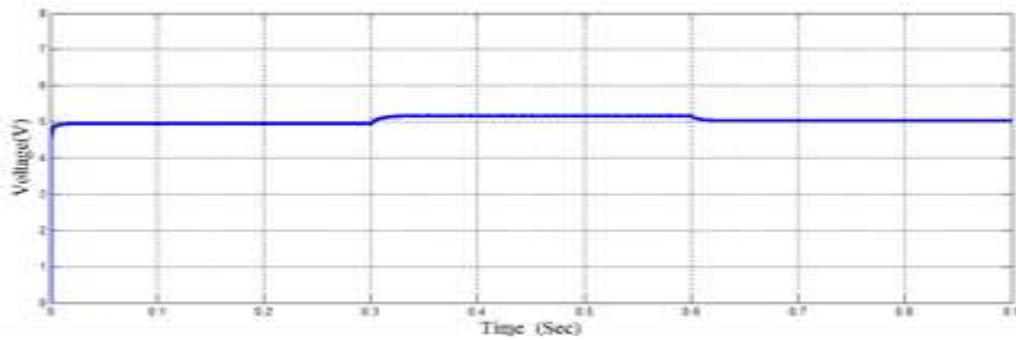

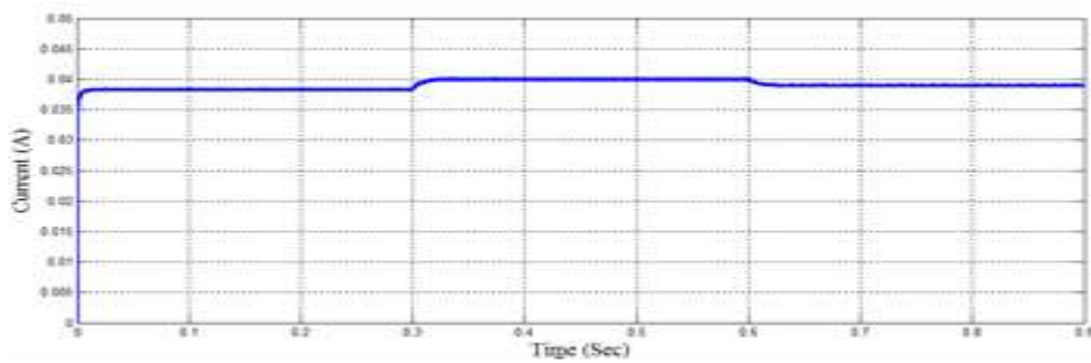**Figure.4h. Output Voltage waveform for PI controllers**

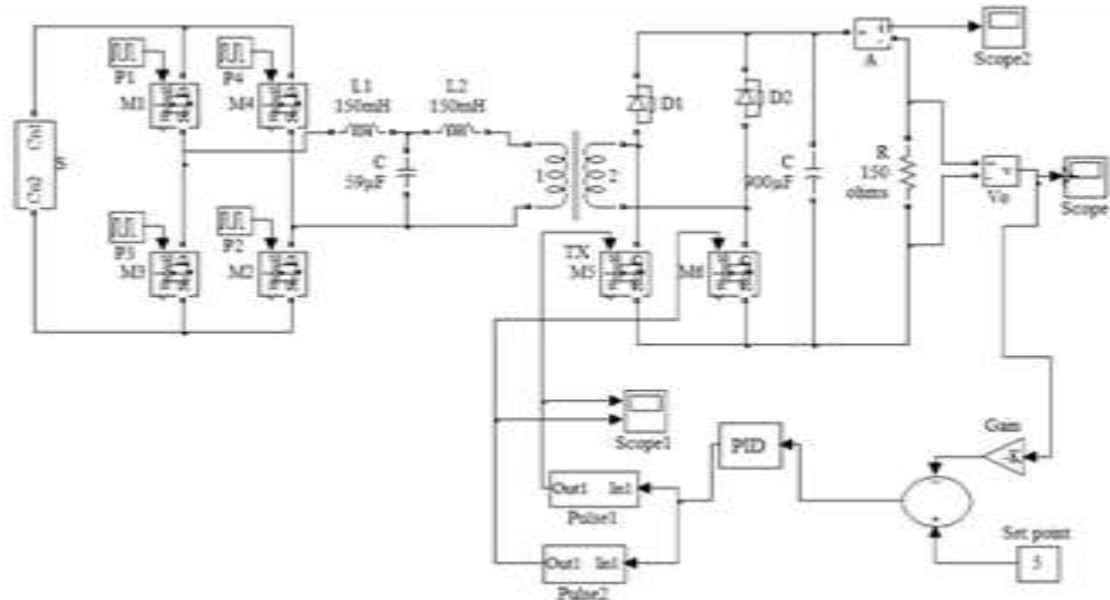**Figure.4i. Output current waveform for PI controllers**

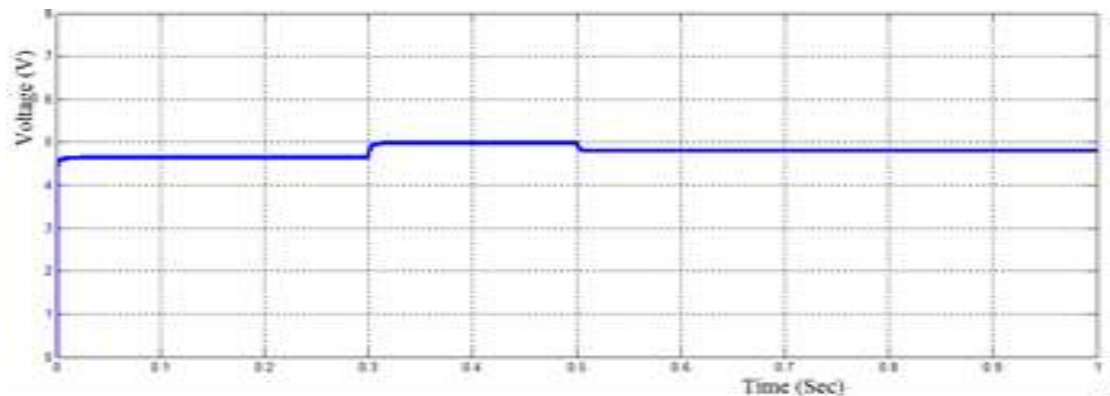**Figure.4j. LCL-T Resonant Converter with the PID Controller**

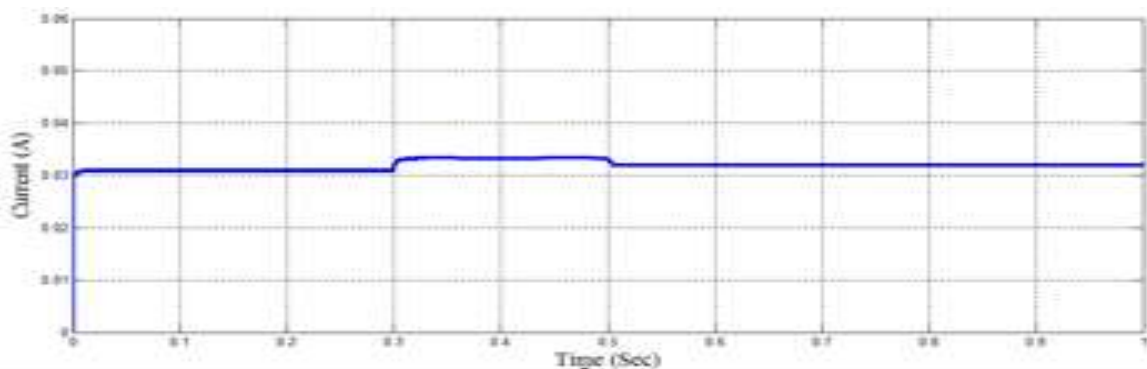**Figure.4k. Output Voltage waveform for PID controllers**

Figure.4l. Output current waveform for PID controllers

The comparison of closed loop response of LCL converter system with PI and PID controllers is given in Table 1. The settling time with PID controller is 18% less than that of PI controller system. The steady state error with PID controller is 50% less than that of PI controller system. Therefore, PID controller is preferred to PI controller in the closed loop.

Table 1: Comparison of Closed Loop response of LCL converter system with PI & PID controllers

LCL Converter	Rise Time (T_r)	Settling Time (T_s)	Peak Time (T_p)	Peak Voltage (V_p)	Steady state error (E_{ss})
PI Controller	0.015	0.61	0.44	0.22	0.016
PID Controller	0.010	0.50	0.40	0.21	0.008

VI. DISCUSSION AND CONCLUSION

The open loop and closed loop controlled DC-DC converter systems for different controllers are simulated using MATLAB version 7.1 and the results are presented. This converter is popular due to reduced EMI, reduced stresses and high power density. The simulation studies indicate that LCL type DC-DC converter can be used with stand-alone wind generator. The simulation results closely agree with theoretical results.Constant voltage can be maintained at the output of DC-to-DC converter by using a PWM rectifier atthe output. Simulation results indicate the validity of closed loop model. From the results the PID controller is preferred for closed loop systems.

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